Guidelines for Operating Traffic Signals during Low-Volume Conditions

Ahmed Abdelghany, Ph.D.
Research Professor
Center for Transportation Research
University of Alaska Fairbanks
P.O. Box 755900
Fairbanks, Alaska, 99775-5900

Billy Connor, P.E.
Director
Center for Transportation Research
University of Alaska Fairbanks
P.O. Box 755900
Fairbanks, Alaska, 99775-5900
Phone: (907) 474-5552
E-mail: ffbgc@uaf.edu

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The main objective of this research is to investigate the performance of flashing traffic signals as a device to control traffic periods with low traffic volumes, particularly during late night/early morning hours. First, the study identifies the main factors that affect the performance of flashing traffic signals. Next, it defines the main guidelines and precautions that should be considered when implementing flashing traffic signals in yellow/red or red/red modes, during late night/early morning hours.

An extensive literature review is presented, which covers several case studies of flashing signal operation. In particular, three main aspects are considered in this review which are: safety and accident rates and types at intersections with flashing signal operation, motorists' comprehension to flashing traffic signals, and available guidelines for using flashing signal operation.

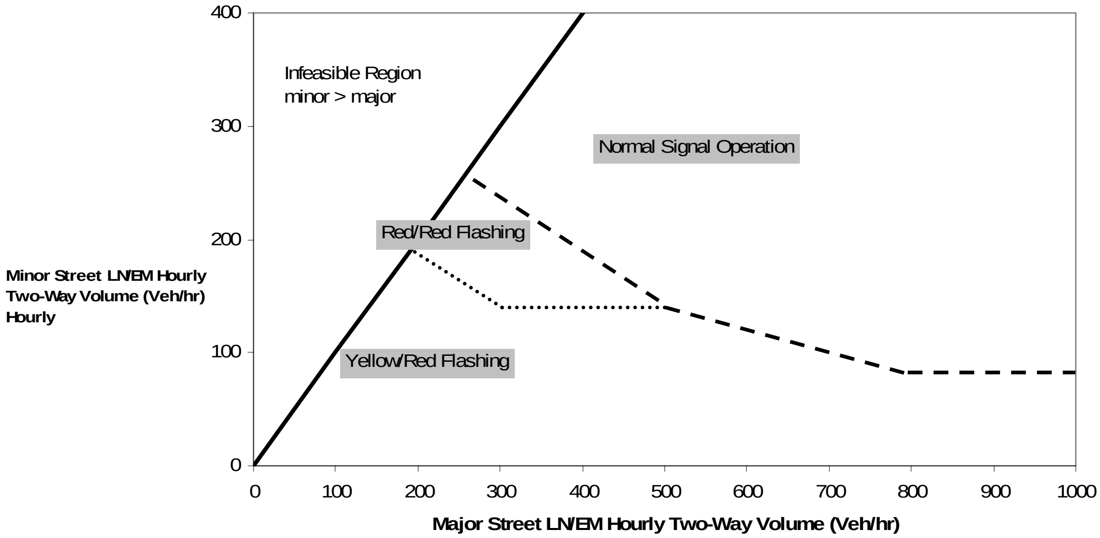
Most of the reviewed studies have reported that flashing signal operation is not safe. It is generally reported that there is an increase in accident rate when flashing signal operation is implemented at various traffic intersections. Literature also reported that significant portion of drivers do not understand flashing signal messages. In many circumstances, they do not know what the correct actions are when they encounter flashing traffic signals. Furthermore, most of the guidelines that warrant the use/elimination of flashing traffic signals are based on only accident rates and/or traffic volumes. A comprehensive list of guidelines is needed to consider all factors that might affect the safety and performance of flashing traffic signals.

Based on the review, the main factors that affect the operational performance of flashing traffic signals in its different modes are identified as follows:

- Traffic volumes on the main and secondary approaches
- Number of lanes by type on each approach
- Average travel speed and speed limits
- Intersection geometrics and stopping sight distance
- Starting and ending time of flashing signal operation

- Land use in the surrounding area
- Traffic composition and existence of pedestrians and cyclists
- Familiarity of travelers with flashing signal operations
- Availability of advisory signs

Next, the study sets the main guidelines that should be considered for implementing flashing traffic signals during late night/early morning hours. These guidelines depend on the factors affect the operation of flashing traffic signals and listed above. To determine the traffic volumes that warrant the operation of flashing traffic signals, the study adopts a methodology similar to the one defined in the Highway Capacity Manual (2000), which determines the appropriate type of traffic control (signal, stop sign, or yield sign) for the different intersections. The methodology is derived from the observation that flashing traffic signal operation mimics the control of traffic at intersections with stop sign and yield sign control. Therefore, it is necessary to make sure that the considered precautions for using stop sign and yield sign operation are available at signalized intersections at which flashing traffic signals operation is implemented during low-traffic volume periods. The methodology is based on the levels of traffic volume on the main and the secondary approaches of the intersection. It requires that the level of traffic volumes that are suitable for red/red flashing traffic signal should be in the range of traffic volumes that work successfully under 4-way stop sign intersection. Similarly, the level of traffic volumes that are suitable for yellow/red flashing traffic signals should be in the range of traffic volumes that work successfully under 2-way stop sign intersections. To consider the special nature of the flashing traffic signal and any special condition at the intersection, a safety factor can be used to adjust (further reduce) traffic volumes that warrant operation of a flashing traffic signal. The following figure shows an illustrative example of the proposed methodology to show how traffic volumes can be used to select between normal signal and flashing signal operations at a signalized intersection. In this figure a factor of safety of 50% is used to further reduce traffic volumes warrants on the approaches of the intersection to take care of any special intersection characteristics or the nature of the flashing traffic signal operation that might cause unsafe operation.


Infeasible Region
minor > major
Normal Signal Operation
Red/Red Flashing
Yellow/Red Flashing
Minor Street LN/EM Hourly Two-Way Volume (Veh/hr) Hourly
Major Street LN/EM Hourly Two-Way Volume (Veh/hr)
0
100
200
300
400
0
100
200
300
400
500
600
700
800
900
1000

1. INTRODUCTION

Traffic signals are control devices that alternately direct traffic to stop and proceed at intersections using automatic red, yellow and green traffic lights. They typically allocate the right-of-way among several conflicting traffic movements at intersections. Objectively, they guarantee vehicular traffic safety as well as the safety of other users, including pedestrians and cyclists. In addition, traffic signals are designed such that the right-of-way is allocated in a fair manner among the different traffic movements, such that the total stopping time (delay) is minimized at the intersection. Traffic signals at adjacent intersections could also be linked and timed together such that they allow continuous traffic flow along main corridors (coordinated systems).

At any intersection, traffic signals usually operate under varying traffic volumes and traffic movements throughout the day. Traffic volumes during the off-peak periods are usually much less than those during the peak periods. Indeed, traffic volumes usually fall sharply during the late night and early morning (LN/EM) hours. Furthermore, traffic volume for each traffic movement in the intersection varies significantly throughout the day. For instance, the majority of the traffic at an intersection could be heading to one direction during the morning peak period and heading to the opposite direction during the afternoon peak period. These observations make it hard to find a single optimal plan for the traffic signal that allocates the right-of-way efficiently among the different traffic movements at the intersection throughout the whole day. The problem is even more intricate for traffic signal systems where the operation of traffic signals is coordinated.

Over the past two decades, advances in control and sensing technologies have expanded traffic signals ability to manage traffic at intersections and along corridors more efficiently and safely under the varying traffic volumes. Therefore, traffic signals can operate in several different modes:

- Pre-timed Operation
- Fully-Actuated Operation
- Semi-Actuated Operation

Pre-timed signals are the simplest type of traffic signals, where the non-conflicting traffic movements in the intersection are usually grouped into phases with each phase given the right-of-way for a predetermined fixed interval. An intersection could be operating under a single pre-timed plan or several plans (e.g. one for the morning peak and another one for the afternoon peak) to match the traffic demand variation over the day. Unlike pre-timed signals, actuated signals can end a phase before it reaches its time limits if the demand is low. They can even skip phases if there is no demand for that phase. For this reason, actuated signals are especially useful in low-demand settings, such as in rural areas or at night. Actuated traffic signals employ sensing technologies to detect traffic on the different approaches and use this information to determine the time during which the right-of-way is allocated to each phase. Actuated signals could be operated in fully-actuated mode or semi-actuated mode. Fully-actuated signals have detectors on all the approaches of the intersection and semi-actuated signals only have detectors on some of the approaches. Actuated traffic signals tend to be more expensive and require additional maintenance considerations for its sensing devices, which makes their deployment always limited by budget constraints.

Traffic volumes observed during late night and early morning hours are typically low, and in most cases, do not warrant the use of traffic signals. Drivers usually report inconvenience of unjustified stopping and delays at signalized intersections during these periods. In addition, observations show that during late night and early morning hours, drivers are willing to overlook stopping at the red traffic signal when the intersecting approaches have no traffic. They usually tend to proceed across the intersection based on their own judgment, raising the risk of accidents.

There has been general disagreement on the best practice to operate traffic signals during the periods of low traffic volumes (late night and early morning hours). If the intersection is supported with the traffic detection technologies, actuated signal operation would be the best practice. Actuated traffic signals can adjust its timing to be compatible with the varying traffic volumes at the different times and efficiently manage traffic on the different approaches to minimize the overall delay. They typically allow continuous flow of the traffic on the main approaches of the intersection, which is only disrupted when traffic is detected on the minor approaches. However, as mentioned above, actuated signals are not available at all signalized intersections. They are usually expensive to be deployed in every intersection and they require more maintenance considerations. The second alternative is to use the pre-timed signal with a plan that is suitable for the low traffic volumes operations (e.g. short cycle length). However, while this alternative might reduce the stopping delay for traffic during the period of low traffic volumes, it was argued that it does not completely eliminate the unjustified stop of traffic at empty intersections.

Another practice that is considerably adopted by different traffic agencies is to use traffic signals to mimic stop/yield sign operations during off-peak periods. This is accomplished by setting traffic signals to operate in the flashing mode. Flashing signal operation is defined as when traffic signals' lenses are illuminated with rapid intermittent yellow or red flashes. Two main plans (modes) are usually applied; red/red and yellow/red. With the red/red plan, both the major and minor approaches of an intersection are given red flashes. In this case, a driver in either approach shall stop before entering the crosswalk on the near side of the intersection. The driver may proceed subject to the rules applicable to stopping at a four-way stop intersection (i.e. first-in-first-out). In the yellow/red plan, the major approach is given a yellow flashing light, while the minor approach is given a red flashing light. In this case, traffic in the main approach shall proceed with caution (without stopping) while traffic in the minor approach should always stop to yield to the traffic in the main approach. Flashing signal operation is also applied during signal malfunctions, maintenance and emergency conditions.

Generally, there is disagreement among practitioners regarding the performance (and particularly safety) of flashing traffic signals. Typically, deployment of flashing traffic signals is widely based on the judgment of traffic engineers with vastly different experience and understanding; and possibly they might not consider of all the factors that can affect the flashing signal performance. This could be the reason that deployment of flashing traffic signals is successful in some locations and not in the others. It is very odd that flashing traffic signals are widely deployed and accepted by traffic engineers all over the U.S., regardless of 1) the absence of rigorous nationwide set of guidelines that identify its appropriate operation scenarios (e.g. traffic volumes, approaches speed, approaches traffic volume ratios, etc.) and 2) the existence of safety performance research that demonstrates whether or not flashing traffic signals are acceptable solutions for periods of low volume at such intersections..

In a study conducted by the Texas Transportation Institute (Kacir et al. 1993), a survey is distributed to the TxDOT districts and local district agencies to gather information about several aspects of flashing traffic signals. In this survey, 70.2 percent of respondents reported that there are signalized intersections within their jurisdiction which use flashing operation. About 46.8 percent of respondents reported that they have no guidelines for flashing signal operation and 91.5 percent never performed an analysis of the effectiveness of flashing traffic signals. Only 8.5 percent indicated that they do not need guidelines for flashing signal operation.

The main objectives of this research are to investigate the performance of flashing traffic signals as a device to control traffic during late night/early morning hours. The study also identifies the main factors that affect performance of flashing traffic signals. Furthermore, it sets guidelines and precautions to be considered when implementing flashing traffic signals in yellow/red or red/red modes, during late night/early morning hours. In the next section, we review previous research that investigated the performance of flashing traffic signals. In particular, three main aspects are considered in this review which are: safety of flashing signal operation, motorists' comprehension for flashing traffic signals, and available guidelines for using flashing signal operation. Based on the review, the following section identifies the main factors that affect the operational performance of flashing traffic signals in its different modes. Finally, the guidelines that should be considered for implementing flashing traffic signals during late night/early morning hours are identified.

2. LITERATURE REVIEW

This section reviews the major research efforts about flashing traffic signals as a traffic control device during the late night/early morning periods. Three main aspects are considered in this review; 1) safety of flashing signal operation; 2) motorists' comprehension for flashing traffic signals; and 3) available guidelines for using flashing signal operation.

2.1 Safety of Flashing Signal Operations

The following subsections summarize the main studies investigating accident patterns, rates, and frequency at intersections with flashing signal operations during late night/ early morning hours.

Polanis (2002)

This study investigates the relation between right-angle crashes and late-night/early-morning flashing operations in nineteen locations in Winston-Salem, NC. These locations had previously been flashing signal intersections during late night and early morning hours but were returned to normal signal operations during these hours after vehicle accident patterns suggested that a return to normal signal operation might reduce crashes. A before-and-after study is performed where the data is analyzed at both the aggregate and disaggregate levels. The number of right-angle crashes and the percentage of right-angle crashes to total number of crashes were recorded for the hours the signal was scheduled to operate in yellow/red flashing operation. Aggregate data analysis (Table 1) shows significant reduction in right-angle crashes when traffic signal operation is changed from flashing mode to normal mode. In the 888 months of before data, 156 right-angle crashes occurred compromised 25.5 percent of 612 total crashes. In the 906 months of after data, 35 right-angle crashes occurred, made up 8.5 percent of the 413 total crashes. Right-angle and total crashes declined by 78 percent and 33 percent in the after period.

Table 1: Summary of crash data aggregated from 19 case studies (Source: Polanis 2002)

Scenario	Months	Right-angle crashes	Total crashes	Right-angle/total
Before	888	156	612	25.5%
After	906	35	413	8.5%
		-78%	-33%	

Table 2 presents the percentage change for the right-angle and total crashes when the data is disaggregated for each intersection. For each location, the ratio of main- to side-street traffic (M:S ratio), the land use around the intersection (Downtown, Residential, and Commercial), and the type of signal controller at the intersection (Fixed type, Semi-actuated, and actuated) are observed. The data from these 19 locations show that removing signals from a programmed flash can reduce crashes. Right-angle crashes decreased at every intersection after late night/early morning programmed red/yellow flash was removed (16 of the 19 reductions in right-angle crashes were statistically significant at the 95 percent confidence limit). Total crashes declined at 14 of the 19 intersections after the signal was removed from yellow/red flash (12 of the 14 reductions in total crashes were statistically significant at the 95 percent confidence limit). The results also show that high ratios of main-street to side-street traffic do not guarantee that the right-angle crashes will decrease. Due to the small sample size, the impact of land use around the intersection and the type of signal controller at the intersection could not be statistically identified.

Finally, the author concluded that flashing traffic signals are a strategy adopted to reduce delay that need not be abandoned, but its use requires careful application and additional monitoring. The authors stated that "Agencies using the strategy should adopt a posture similar to that of a physician prescribing a drug to treat a specific ailment that has possible adverse side effects (i.e. do the appropriate monitoring to assure the treatment to cure one ailment does not cause another)", Polanis (2002).

Table 2: Summary of individual crash-data case studies (Source: Polanis 2002)

Case #	Before			After			Δ% right-angle	Δ% total	M:S ratio	LU	ST
	Months	Right-angle Crashes	Total Crashes	Months	Right-angle Crashes	Total Crashes					
01-87	50	15	79	45	8	29	-41	-59	2:1	D	F
02-87	33	5	18	48	0	10	-100	-62	2:1	R	S
02-88	43	8	39	41	5	21	-34	-44	2:1	R	F
05-90	48	8	26	48	3	26	-62	0	NA	R	F
06-90	45	12	23	45	2	25	-83	9	2:1	C	A
07-90	48	12	23	48	1	8	-92	-65	1:1	D	F
22-91	58	12	31	80	1	28	-94	-34	5:1	R	S
29-92	46	6	17	43	4	14	-29	-12	2:1	R	S
32-92	82	9	80	78	1	49	-88	-36	2:1	C	A
05-93	22	4	10	22	0	4	-100	-60	4:1	D	F
09-93	48	8	26	48	1	14	-88	-46	1:1	R	A
04-93	48	7	32	48	2	17	-71	-47	3:1	C	F
08-93	49	9	35	47	0	23	-100	-32	3:1	C	A
16-93	46	4	23	46	2	18	-50	-22	1:1	R	A
02-95	51	11	44	49	1	26	-90	-38	2:1	C	A
43-96	46	4	13	45	1	16	-74	26	1:1	R	A
48-96	45	8	25	45	2	32	-75	28	2:1	C	A
06-98	44	5	11	44	1	12	-80	0	4:1	D	F
02-98	36	9	57	36	0	41	-100	-28	3:1	D	F

Key

- Right-angle crashes -- right angle crashes that occurred during the hours the signal was in red/yellow flashing mode
- Δ% right-angle and Δ% total -- refer to the percentage change in right-angle and total crashes in the before and after periods (measured in crashes/month)
- M:S – this is the ratio of main-street to side street traffic volumes at each intersection
- LU – Land use around the intersection (D: Downtown, R: Residential and C: Commercial
- ST – Signal type (F: Fixed time, S: Semi-actuated, and A: Actuated)

Kacir et al. (1993) and Kacir et al. (1995)

This study is one of the most comprehensive studies that evaluated several aspects of the flashing signal operation at signalized intersections. This study was conducted by the Texas Transportation Institute in cooperation with the Federal Highway Administration and Texas Department of Transportation (1993) with several activities including: a literature review of previous flashing signal research, a survey of the current practice related to flashing signal operation, an operational analysis comparing flashing signals to other types of signal operation, and an investigation of accident trends for flashing traffic signals. A series of guidelines were developed addressing the appropriate conditions for traffic signals to be in flashing operations as well as which flashing mode (yellow/red or red/red) is appropriate.

As part of this study, a survey is administrated to traffic engineers throughout the State of Texas to collect information about the operation of flashing signals. Information on each intersection that currently flashes or had flashed within the last ten years was collected. Other pertinent information requested included: the date of flashing implementation or flash removal, time of day for flashing operation, and day(s) of the week the signal operates in flashing mode. From the responses, potential study sites were identified for both urban and rural locality representation.

The site selection for the accident trends study was limited to four-leg, bi-directional signalized intersections. To exclude as much uncertainty as possible, a near perfect geometric configuration was sought. Initially 200 intersections were identified as meeting the selection requirements. The data set was divided into three primary groups: 1) continuous flashing operation, 2) locations that had operational change, and 3) 24-hour normal operation. The continuous flashing operation group contained signals that flashed continuously throughout the study period. The before-and-after group contained signals that were changed from normal operation to flashing operation or vice versa sometime during the study period. Accident records were collected and compiled from January 1985 through December of 1992. For intersections that had signal operation change, a four-year period was available to evaluate the effect of the change, further reducing the number of intersections into 171. About 37% of these intersections had flashing operation implemented or removed between 1986 and 1991. About 16% of these intersections operated on 24-hour normal operation between 1986 and 1991 and 47% had flashing operation prior to 1986. Based on the population, the intersections were also grouped into urban and rural categories. In this study, accident frequency, which reflects the number of accidents that occur during a time period, is used to evaluate the control performance at the intersections.

Accident analysis results showed that the rural category did not provide any observations during the nighttime period; therefore, a statistical analysis of the intersection accident frequencies and collision severity was not possible. Table 3 shows the number of accidents collected for the different urban intersection (classified based on the type of signal control). Generally results indicated an increase in the number of accidents when signals changed from normal operation to flashing operation. There is an increase in the number of accidents 13 in the before-period to 32 in the after-period. Also, during the after study period, there was sharp increase in the number of accidents for the intersections that were working continuously in the flashing mode. The number of accidents increased from 2 in the before-period to 12 in the after-period.

An analysis was performed to investigate the accident type. During nighttime in urban areas, angle-collisions were found to be the most increasing type of collision at the intersections where flashing signals were implemented. These results are presented in Table 4, which lists the accidents by type and severity for different intersection geometry. Intersections are grouped based on the number of lanes on each approach into three groups. Group A represents the intersections with 2 lanes by 2 lanes (2x2). Group B represents intersections that are larger than 2x2, but less than 6x6. Finally, Group C represents intersections that are 6x6 and larger. The only significant conclusion is the increase in right-angle crashes at intersections with flashing signal operation during the nighttime. However, due to the small sample size the impact of the intersection size could not be evaluated.

Table 3: Urban Area Nighttime Accident Frequencies (Source: Kacir et al. 1993)

Time Period	Number of Accidents for Each Intersection Control Group			
	Group 1a Normal/Flash	Group 1b Flash/Normal	Group 2 Normal/Normal	Group 3 Flash/Flash
Before (2 years)	13	1	12	2
After (2 years)	32	0	13	12
Total Accidents	45	1	25	14

Table 4: Urban-area Nighttime Accident Frequencies for Intersections where Flashing Signals were Implemented (Source: Kacir et al. 1993)

Accident Categories		Intersection Geometry Groups					
		Group A 2x2		Group B (>2x2, < 6x6)		Group C (≥ 6x6)	
		Before	After	Before	After	Before	After
Type of Collision	Rear-end	0	0	0	0	2	0
	Angle	1	0	7	27	0	3
	Other	0	0	0	2	3	0
Accident Severity	Incapacitating Injury	0	0	0	3	1	0
	Non-Incapacitating Injury	0	0	3	6	3	0
	Possible Injury	1	0	4	9	0	2
	Fatality	0	0	0	1	0	0
	Property Damage Only	0	0	0	10	1	1
Total Number of Accidents		1	0	7	29	5	3

Akbar and Layton (1986)

This study investigated flashing operations by analyzing accidents at thirty intersections in Portland, Oregon. The city of Portland was selected for the study because of available accident data for nighttime flashing traffic signals in 1981 and in early 1982. Flashing operations were terminated in late 1983 as a result of the increase in accidents. The thirty intersections that had been changed from normal to nighttime yellow/red flashing operation were returned to regular, full-color nighttime operation.

The different intersections are classified into several categories and before-and-after accident data (one or two years) is collected for each category. The intersections categories are based on several intersection characteristics including:

- Volume ratios: zero to twice as much volume on the major street approach as on the minor street approach, two or four times the volume on the major, and more than four times greater major street volume
- Street classification: an arterial intersection with a collector, arterial with a collector, collector with a local, collector with a collector, local with a local, arterial with a local or collector.
- Type of approach: two-way to two-way, two-way to one-way, one-way to one-way.
- Speed limit: posted approach speed less than or equal to 30 miles per hour (mph) and greater than 30 mph.
- Presence of parking: parking and no parking.

Accident data was split based on accident type and accident severity and accident rates were calculated for each intersection. These rates represent the average number of accidents per million vehicles passing through the intersection for each location. The analysis evaluated two-accident types; rear-end and angle and two severity classes; property damage only and injury. A measure of relative accident severity was given by a severity index (SI), which is the proportion of accidents in which an injury or a fatality occurs.

The evaluation of the safety characteristic changes was based on a comparison of their respective means. When two means differed markedly, little problem existed in deciding whether there was a significant change. However, when the difference was small, there was always a question of whether the change was due to change variation in the data rather than to the improved conditions. The effectiveness of the traffic improvement was judged by a statistical evaluation of the before-and-after data to determine whether the changes were significant.

The analysis shows that the volume ratio had an impact on the safety under flashing operations (Table 5). At intersections with major-street volumes between two and four times the minor-street volume, significant increase in accident rates occurred with flashing-signal operation compared with normal full-color signal operation. It is suggested that drivers at these intersections expect drivers on the major approach to also receive a flashing red because, under full-color operations, both streets are treated equally.

Intersecting streets classification also had an effect. The intersections between arterial and a collector, a collector and a local, and a local and a local indicated a significant increase in accidents for flashing operation when compared with regular signal operation. The mean accident rates for regular signal operation were considerably lower than those for flashing-signal operation (Table 6). Arterials intersections with collectors also experienced increased accident severity, with severity indices of 0.0 and 0.25 for regular and flashing operations, respectively. Local street/local street intersections experienced the greatest increase in accident severity; the severity index increased from 0.0 to 0.9 from regular to flashing operation. A severity index of 0.9 for this intersection condition means that 90 percent of the accidents at this intersection involved an injury or fatality.

The next variable tested was the type of approach, which showed that intersections between two 2-way streets had significantly lower accident rates with regular signal operation (Table 7). With the higher conflict level present at intersecting two-way streets, it becomes difficult for the driver to keep track of all conflicts to react safely.

The analysis of the effect of major-approach speed on accident rates revealed a significantly higher accident rate for angle and injury accidents with a considerable increase in mean accident rate for the flashing signal operation. The increase in right-angle accidents was highly significant for approach speeds of more than 30 mph, which is an expected result. With full-color operation there is more positive control of the assignment of the right-of-way. The lack of such control with flashing operations would be expected to generate more right-angle collisions. With higher approach speeds, the driver does not have as much time to react, and the potential for accidents increases. Higher impact speeds and right-angle collisions would be expected to increase the rate of injury accidents. Table 8 summarizes the change in the rate of accidents for the two categories of approach speed.

Studying the effect of parking was not completely successful due to the lack of reliable information on the nature of parking at the time that the data were collected. However, from the data available (see summary in Table 9), it could be concluded that when there is parking on both sides of the major and minor streets, signals at intersections should not be operated in the flashing mode. It is likely that the presence of parking at these locations reduces the visibility to below accepted sight distances for safe operation.

The study concluded that the increase in accidents in the flashing period might be a result of the drivers' difficulty in judging when it is safe to proceed. However, drivers might also be confused by the nighttime flashing operation because they do not anticipate that the right-of-way has been given to the other street and that only the minor-street traffic is required to stop. An attempt to improve driver understanding with a public awareness campaign or special signing should be made and flashing operations should be allowed to continue only if accident experience improves.

Table 5: Analysis of Accidents for Intersections with Various Traffic Volumes (Source: Akbar and Layton 1986)

Accident type	Mean Accident Rate		Standard Deviation		t-Statistic
	Full Color	Flashing	Full Color	Flashing	
Volume Ratios Less than 2.0 (N=4)					
All	3.29	1.06	6.58	2.12	0.645
Volume Ratios Between 2.0 and 4.0 (N=14)					
All	1.2	5.44	2.32	5.39	-2.704
Volume Ratios Greater than 4.0 (N=12)					
All	1.89	2.75	2.20	3.79	-.688

Table 6: Analysis of Accidents for Intersections with Various Street Classifications (Source: Akbar and Layton 1986)

Accident type	Mean Accident Rate		Standard Deviation		t-Statistic
	Full Color	Flashing	Full Color	Flashing	
Arterial/Collector (N=2)					
All	1.02	12.02	1.43	0.26	-10.688
Arterial/Local (N=4)					
All	4.63	3.78	5.91	4.37	0.231
Collector/Local (N=11)					
All	0.55	2.14	1.30	3.81	-1.309
Collector/Collector (N=6)					
All	4.34	4.14	2.93	5.56	0.078
Local/Local (N=7)					
All	0.00	3.71	0.00	4.19	-2.343

Table 7: Analysis of Accidents for Intersections with Various Types of Approaches (Source: Akbar and Layton 1986)

Accident type	Mean Accident Rate		Standard Deviation		t-Statistic
	Full Color	Flashing	Full Color	Flashing	
Two-Way/Two-Way (N=15)					
All	1.88	6.18	3.48	5.24	-2.647
Two-Way/One-Way (N=10)					
All	2.45	1.40	3.13	2.52	0.824
One-Way/One-Way (N=5)					
All	0.00	1.36	0.00	1.95	-1.557

Table 8: Analysis of Accidents for Intersections Grouped by Approach Speed (Source: Akbar and Layton 1986)

Accident type	Mean Accident Rate		Standard Deviation		t-Statistic
	Full Color	Flashing	Full Color	Flashing	
Major-Approach Speed Limit < 30 mph (N=22)					
All	1.61	3.36	3.27	4.15	-1.554
Major-Approach Speed Limit > 30 mph (N=8)					
All	2.16	4.18	2.73	5.27	-0.962

Table 9: Analysis of Accidents for Depending on Presence of Parking (Source: Akbar and Layton 1986)

Accident type	Mean Accident Rate		Standard Deviation		t-Statistic
	Full Color	Flashing	Full Color	Flashing	
Parking Allowed on Both Streets (N=16)					
All	2.24	5.07	3.75	5.16	-1.773
Parking Allowed on One Street (N=8)					
All	1.85	2.44	2.64	4.70	-0.309
No Parking Allowed on Either Street (N=6)					
All	0.34	2.16	0.84	1.88	-1.162

Barbaresso (1984 and 1987)

In this study, the relative accident impacts of flashing and normal signal operation in Oakland County, Michigan were evaluated. Analysis was conducted to determine if an accident problem exists at intersections where signals are in a flashing mode during off-peak nighttime hours. The study also investigated what levels of accident experience can be expected under different conditions and signal operations. In the two-staged study, the first stage consisted of a before-and-after study of six signalized, four-legged intersections. The sites of these intersections were chosen at random from a listing of pre-timed signals where flashing operation had been eliminated. The only restrictive criterion in the selection of the study sites was that accident data to be available for three years before and after the signal operation change. Paired t-tests were performed for the six study sites to determine if accident frequency and accident rate per million vehicles changed significantly in the after period. Accident types were categorized as right-angle accidents, left-turn accidents, rear-end accidents, and other accidents. An additional 10 intersections, where signals remained on flash operation during off-peak nighttime hours throughout the study period, where randomly selected to provide a control group for the before-and-after study and to supplement the analysis of other factors that may have some influence on accident levels. These factors include the hourly intersection traffic volume, main street hourly volume to minor street hourly volume (the volume ratio), and drinking involvement.

The results of both the before-and-after study clearly indicated that significant reductions in nighttime right-angle accident frequency and rate can be attained by eliminating flashing signal operation (see Table 10). Other results as summarized by the researchers include:

1- The rate of right-angle accidents for volume ratios of 2 to 1 or less was significantly higher than the rate for volume ratios of 4 to 1 or greater at flashing signal locations.

2- Surprisingly, the study concluded that hourly intersection traffic volumes had a negligible impact on right-angle accident frequency during hours of flashing operations.
3- Drinking involvement was significantly over-represented in right-angle accidents at flashing signal locations.
4- Right-angle accidents at flashing signal locations peaked between midnight and 3 a.m., after which they dropped dramatically. Right-angle accidents at normal-operation locations peaked between 2 and 3a.m.; the author notes that bars close at 2a.m. in Michigan.
5- Although it was found that rear-end accident frequency was significantly higher at normal operation locations during late night hours, no significant difference in rear-end accident rates per million vehicles was found between the two operating modes. Therefore, the difference in rear-end frequencies may be attributable to the relative volumes of traffic at normal operation and flasher locations.

Table 10: Before-and-After Right-Angle Accident Frequency per Year-Hour and Right-Angle Accident Rate per Million Vehicles of Signal Operation (Source: Barbaresso 1987)

Site	Right-Angle Accident Frequency per Year-Hour		Right-Angle Accident Rate per Million Vehicles	
	Before	After	Before	After
1	0.417	0.083	6.31	1.26
2	1.083	0.000	35.06	0.00
3	0.250	0.000	16.31	0.00
4	0.292	0.042	3.90	0.56
5	1.400	0.000	6.83	0.00
6	1.500	0.000	13.11	0.00
Total	4.942	0.125	81.52	1.82
Mean	0.824	0.021	13.59	0.30

The second stage of the analysis compared the mean right-angle accident rates and frequencies of the flashing and the normal signal control types. Flashing signal locations were categorized by intersection type (four-legged-right-angle and three-legged-T) and the functional classification of the intersecting roadways (arterial-arterial and arterial-collector). For each of these intersections types, the mean frequency and rate of right-angle accidents per year-hour were calculated for hours with flashing signals. T-tests were conducted to determine if the means differed significantly from each other and from the mean for the hours of 11 p.m. to 6 a.m. at a sample of 21 four-legged intersections where the signals operate on a normal basis. Accident data for 3 years were analyzed for all intersections. The results clearly indicated that significant reductions in nighttime right-angle accident frequency and rate can be attained by eliminating flashing signal operation at four-legged intersections of two arterial roadways. Four-legged intersections of arterial roadways where signals flash during off-peak, nighttime hours experienced significantly greater frequencies and rates of right-angle accidents than other intersection types.

Gaberty II and Barbaresso (1987)

As a result of 1983 Barbaresso study, Board of Oakland County Road Commissions in 1984 adopted and directed the implementation of a Road Commission Policy, from which signals at 60 four-legged intersections of two arterial roads were changed from nighttime flashing to 24-hour full cycle operation. The 1987 study was performed to assess the accident rate following the elimination flashing traffic signal operations. This study was designed to update and validate a preliminary study conducted in 1983 in Oakland County, Michigan (Barbaresso 1984). Fifty-nine of the 60 intersections affected by the policy met the following criteria and were thus chosen for a before-and-after accident study. 1) No major improvement was made to the intersection that might have influenced accident patterns during the study period. 2) At least three full years of accident data were available for the period before the date of signal operation change. 3) At least one full year of accident data was available for the period after the date of signal operation change.

Right-angle and rear-end accident data for the "before" period of flashing signal operations and for the same hours in the "after" period of full-cycle signal operations were extracted from the data and used in the statistical analysis. A cursory inspection of the before-and-after data revealed a substantial decrease in the number and severity of right-angle accidents during the study period (Table 11). For example, before the signal operation change (1980-1983), 202 right-angle accidents occurred, 3 of which involved fatalities and 124 of which involved serious personal injury. In the "after" period (1984 through September 1985), only 8 right angle accidents occurred, with no fatalities and with only 3 personal injury cases. Rear-end accident frequencies were also reviewed; data indicated a slight increase in the frequency of rear-end accidents at the 59 target locations and a slight decrease in the severity of those accidents.

T-test statistical analysis determined whether the "before" mean of a group of locations is significantly different from the "after" for those locations. The tests concluded that changing signal operation from flashing to full cycle at these locations was effective in reducing the frequency of total right-angle and personal injury right-angle accidents during nighttime hours. In addition, there is no significant difference exists between the means of the before and after groups for both total rear-end and personal injury rear-end accidents. Therefore, this program did not affect the frequency of total rear-end or personal injury rear-end collisions.

Table 11: Average Annual Frequency of Right-angle and Rear-end Accidents (Source: Gaberty II and Barbaresso 1987)

Signal Operation	Right-Angle			Rear-End		
	Fatal	Total	Personal Injury	Fatal	Total	Personal Injury
Flashing	50.50	0.75	31.00	7.75	0.00	2.25
Full -Cycle	4.57	0.00	1.71	10.29	0.00	1.75

Benioff et al. (1980)

This Federal Highway Administration (FHWA) study is the earliest most comprehensive study of flashing traffic signal operation. As part of this research, two studies examined separate accident data to determine trends related to flashing and non-flashing signalized intersections. The two studies were identified as 1) the San Francisco study and 2) the national study (Kacir et al. 1993). Several accident types were evaluated including rear-end, right-angle, approach turn, pedestrian/bicycle, and other collision trends. Also, accident severity was evaluated for personal damage only, personal injury, and fatality classifications.

San Francisco Study

During the period of 1974-1977, San Francisco was in the process of converting a large number of its signals to nighttime flashing operations. A computerized accident file was used to compile accident data during this period for 520 intersections in the city and County of San Francisco. These 520 intersections were classified as follows: 375 intersections changed operations from normal to yellow/red flash, 36 intersections changed operations from normal to red/red flash, 107 intersections had no operational change, and 2 intersections changed operations from yellow/red flash to red/red flash. Accidents data was split into two groups based on the time at which they occurred: 1) between 6 a.m. and midnight and 2) between midnight and 6 a.m. Accident rates per day were calculated for intersections grouped by the type of operational change made during the study period. Accident rates were compared for before-and-after periods established by the date of operational change. A chi-square test statistically tested for changes with accident rates. An expected accident frequency was calculated based on the number of days of exposure and compared to the observed frequencies.

The results indicated a statistically significant increase in right-angle accident rates only for intersections where normal operation had been replaced by yellow/red flashing operation. As for accident severity, there was a significant increase in property damage only accidents and personal injury accident rates for the same operational change. There was no significant change in accident rates for the 107 intersections that did not change operation.

Another set of analysis was performed but only included intersections that had at least one accident in either before or after period. The data set consisted of 202 intersections that changed from normal operation to yellow/red flash, 19 intersections that changed from normal operation to red/red flash, 60 intersections that had no operational change, and 2 intersections that had yellow/red flash changed to red/red flash. The study subdivided each operational group (normal, red/red, yellow/red) by intersection location in urban areas, signal system type, and intersection geometry. Intersection location was divided into the following categories: central business district industrial, outlying business district, high density residential and low density residential. The signal system type was divided into arterial and network systems. Intersection geometry was divided into four-leg, three-leg, and more than four-leg groups.

The second analysis revealed similar results to those obtained in the first analysis. For locations where normal operations had been replaced with yellow/red flash, the analysis found significant increases in right-angle, property damage only, and personal injury accidents rates in at least one subdivision of all classifications (i.e. intersection location, signal system type, and intersection geometry). For the same operational change, right-angle collisions increased in the central business district, industrial district, outlying business district, and high density residential locations. Both arterial and network system intersections had significant increases in right-angle accident rates when yellow/red flashing operations were used. Also, in the geometric classifications, four-legged 90-degree intersections showed a significant increase in the right-angle collision rates for yellow/red flashing operations.

National Study

Similar analysis was conducted for accident data collected for 94 intersections throughout the country. The national analysis also used a before-and-after study approach; however, it included intersections that did not observe accidents during the study period.

This analysis used a three-year before and one-year after study period. The selected sample size was reduced to 59 test locations for the study period. Accidents at the selected study locations were analyzed by grouping intersections under the same intersection characteristics as the second San Francisco study then calculating accident rates per million vehicles entering the intersection. A volume ratio (major street volume to minor street volume) test was also used to analyze the study sites. The volume ratio test grouped the data by the ratio of major street volume to minor street volume for the traffic volumes during flashing operation. The analysis of the 59 intersections concluded similar results as the first two San Francisco studies. Right-angle accident rates were higher for intersections in the outlying business district and high density residential locations and as well as in four-legged 90-degree intersections. However, the analysis of accident severity revealed a significant increase for only four-legged 90-degree intersections. In addition, the results from the volume ratio analysis revealed significant increases in right-angle accident rates for volume ratios between two and three.

The main findings of the FHWA study, as summarized by Barbaresso (1987), were as follows:

- Right-angle accidents were significantly higher at intersections with flashing signal operation than at intersections with normal operation.
- Right-angle accidents were significantly higher at flashing signal intersections when the ratio of the of main street volume to side street volume was less than 3:1
- Main street hourly volume demonstrated a significant impact on right angle accident frequency at flashing signal locations
- Rear-end and crossing conflicts were significantly greater at flashing signal intersections than at intersections with normal signal operation.
- Flashing operation resulted in less vehicle delay than the normal signal operation.

Based on the findings of the different studies presented above, it could be easily concluded that the safety of flashing traffic signals, especially yellow/red flashing mode is questionable. Most of the research showed a statistically significant increase in accidents and especially right-angle accidents, when implementing yellow/red flashing signal. In addition, most of the research tried to identify the relation between different intersectional characteristics and accident rate when using flashing traffic signals. Several variables have been investigated, which include vehicular traffic volume on the major/minor approach, vehicular traffic volume ratio (major approach traffic volume/minor approach traffic volume), intersection classification or number of lanes on each approach, posted speed limit, surrounding area type (Rural, urban, Central business district, residential, industrial, etc.), parking availability or sight distance, and time of operation. Due to small sample size after intersections categorizations, only few factors proved statistically to be affecting accident rate at intersections with flashing traffic signals. These factors include main street volume, volume ration, intersection classification, number of maneuvers, and approaches speed.

2.2 Motorists Comprehension of Flashing Signal Operation:

Several studies have been conducted to investigate the level of motorist comprehension of the different traffic control devices that might be confusing to motorists. As part of these studies, motorist understanding of the flashing signals operation was also studied. In the following subsections, description and conclusions of these studies are summarized.

In an earlier study performed by the Texas Transportation Institute (Koppa and Guesman 1978), a picture showed an intersection with a flashing yellow beacon was presented to interviewed motorists. Motorists were then asked what color beacon the cross street would have. While a majority (54 percent) correctly thought that the cross street would have a red indication, sizeable percentages selected incorrect responses. About 17 percent of respondents thought the cross street would also have a flashing yellow indication and the possibility of a red or yellow flashing indication was selected by 26 percent.

Another study (Womack et al. 1981) tested the motorists' comprehension of both flashing yellow and flashing red intersection control beacons in a multiple choice survey. The question on the red beacon asked for the proper response to the beacon, with 87 percent selecting the correct answer. The question on the yellow beacon asked what color the intersecting traffic would see, with 54 percent selecting the correct response. The yellow beacon was also shown in both surveys with an open-ended response. When shown a film of the signal, 98 percent of the drivers were able to give the correct driving response to the signal. When asked about the color of the beacon for intersecting traffic, 84 percent knew that it would be red.

A study conducted by the Texas Transportation Institute (Womack et al. 1993) found that red and yellow flashing beacons are not understood by motorists compared to other signal indications. As shown in Table 12, about 41 percent and 54 percent of respondents gave incorrect answers to questions related to these signal indicators, respectively.

Table 12: Comprehension of Traffic Signal Indicators: Survey Results (Source: Womack et al. 1993)

Signal Indication	Percent Correct	Percent Incorrect	Percent Not Sure
Yellow Arrow – Traffic Signal	80.4	13.2	6.4
Flashing Yellow Ball	80.7	18.1	1.2
Flashing Red – Intersection Beacon	**41.1**	**54.8**	**4.1**
Flashing Yellow – Intersection Beacon	**54.0**	**40.8**	**5.2**
Steady Red X – Lane-Use Control Signal	74.9	6.1	19.0

In this study, interviewees were asked the following two questions regarding the flashing signal operation and were given several possible answers. The percentages of respondents selected each possible answer are also given:

If your direction of travel faces the blinking red light, what color light would the intersecting traffic see?

Blinking red (13.8%)
Blinking yellow (41.0%)
Either red or yellow, depending on the intersection (the correct answer) (41.1%)
Not Sure (4.1%)

If your direction of travel faces the blinking yellow light, what color light would the intersecting traffic see?
Blinking red (the correct answer) (54.0%)
Blinking yellow (14.1%)
Either red or yellow, depending on the intersection (26.7%)
Not Sure (5.2%)

As indicated in the two questions, intersection control beacons were surveyed in terms of the driver expectancy of right-of-way assignment. The survey did not address whether or not the driver knew the correct response to a flashing red beacon, rather asked the driver the colors that the intersecting traffic would see. Generally, the given responses show a great level of unfamiliarity with the color combinations on beacons. It was also found that the mistakes in answering the questions were more often made by the youngest (under 25) and the oldest (over 75) drivers surveyed. Education was also a factor; respondents with less than a high school education were incorrect more often. Additionally, ESL respondents and those with fewer years of driving experience were less likely to give the correct response. Similar responses were also found by the FHWA study (Benioff et al. 1980). When drivers were asked about the possible action of traffic in the cross street, if he/she faces a flashing red signal, only 33 percent of respondents gave the correct answer. Generally, the results indicate that motorist comprehension of flashing signal messages is not complete, particularly for yellow/red flashing signals. Typically, a significant portion of motorists are confused about the appropriate action when prompted by a flashing signal to proceed through intersections.

2.3 Available Guidelines for Flashing Signal Operations

Most of the studies that investigated the accident trends and the operation performance of flashing traffic signals have suggested guidelines for using flashing signal operations. These guidelines were based on the accident results of these studies, and as the studies varied in detail, guidelines differ in the detail level depending on how comprehensive the study. In the following subsections, the main guidelines for flashing signal operation are summarized.

Federal Highway Administration Study (1980)

The FHWA study derived the following guidelines for using flashing signal operation:

- Flashing signal operation should be considered when main street hourly volume is less than 200 vehicles per hour (vph).
- Flashing signal operation may be used when main street hourly volume exceeds 200 vph if the volume ratio is greater than 3:1.
- Flashing signal operation should be eliminated if the following parameters reached or exceeded at an intersection:
    - Three right-angle accidents in one year during flashing operation,
    - two right-angle accidents per million vehicles during flashing operation, if the rate is based on the average of three to six right-angle accidents per year, or
    - 1.6 right-angle accidents per million vehicles during flashing operation, if the rate is based on an average of six or more right-angle accidents per year.

Akbar and Layton (1986)

Akbar and Layton recommended the following considerations when placing traffic signals in the flashing mode:

- Flashing-signal operation may be used with low-volume conditions when the major street to the minor street volume ratio is less than or equal to 2.0.

- Flashing signal operation can be used where approach speeds exceed 30 mph only after careful study and with monitoring of operations and accident experience

- Traffic signals in the flashing mode should not be used at intersections of two-way streets without careful study of the visibility at the location and a monitoring of its operation.

- A study regarding impaired visibility due to the presence of parking should be made to gain better understanding of this influence on flashing-mode operation and performance.

Gaberty II and Barbaresso (1987) and Barbaresso (1984 and 1987)

Barbaresso (1987) summarized several issues and factors that should be considered when considering flashing traffic signals. Because the results of his study indicated that right-angle accident frequency is significantly higher at four-legged arterial intersections when signals flash during nighttime hours, it was concluded that the hourly frequency of right-angle accidents should be a primary factor in the development of criteria for eliminating flashing signal operation.

Right-angle accident frequency provides a basis for reacting to an accident problem by alerting the flash schedule. However, the author commented that right-angle accidents during flashing signal operation are rare events, and some locations that exhibit conditions favoring right-angle accident occurrences may experience accident during the review period. The results indicate that a high risk situation occurs at four-legged intersections of two arterial roadways when traffic signals are in a flashing mode. Therefore, functional classification and intersection configuration provide appropriate surrogate criteria for making signal operation changes during nighttime periods. Although they were not analyzed in this study, arterial intersections with more than four legs should also be considered for the elimination of flashing operation.

Other factors related to right-angle accidents at flashing signal locations include the time of night and the volume ratio. As indicated by the accident analysis, right angle accidents at flashing signal locations dropped dramatically after 3a.m. In addition, four-legged intersections with hourly volume ratios less than 2 to 1 demonstrate significantly higher rates of right-angle accidents than those with ratios greater than 4 to 1 when signals are flashing.

Although sight distance was not analyzed in this study because none of the sample flashing signal locations exhibited sight restrictions from stopped positions, eliminating flashing operation of signals at intersections where sight distance is limited should be considered. Minimum sight distance can be determined using the computational procedures outlined by AASHO (AASHTO (1990)).

Although eliminating flashing signals can reduce right-angle accidents, it must be weighed against the expected advantages; delays will increase as well as the number of rear-end accidents, but rear-end accidents are generally less severe than right-angle accidents and disadvantages like increased delay can be minimized through signal optimization, synchronization, altering cycle length, or semi-actuation.

Eliminating flashing signal operation will also increase hydrocarbons and carbon monoxide emissions. The total tonnage increase of these pollutants would be significant when analyzing all intersections in question for a period of 1 year or longer. However, short-term (1 to 8 hours) concentrations should not measurably change, and people will not be affected by an increase in air pollutants.

Human factors must be considered when making signal operation changes during off-peak, nighttime hours. Of preliminary importance in this regard are (a) driver impairment, (b) driver expectation, and (c) driver frustration.

Right-angle accidents involving impaired drivers are overrepresented at flashing signal locations relative to locations with normal signal operation during the same nighttime hours. This conclusion may indicate a possible perception problem for impaired drivers when faced a flashing signal. Further research is necessary to determine if this is the case. Regardless, driver impairment must be considered. Signals are normally placed on flashing operation during time periods when drivers are most apt to be tired or under the influence of drugs or alcohol. Normal signal operation should be considered until at least 1 hour after bars close.

Another factor to consider is driver expectation. A well-established practice in traffic engineering is to provide drivers with uniform traffic control devices, thereby decreasing driver confusion and enhancing driver expectancy. Flashing signals provide drivers with a set of stimuli that differ from those that they encounter during normal daytime living. This may lead to confusion of drivers faced with a flashing signal.

Finally, driver frustration can be expected when drivers are forced to stop for signals during nighttime, low-traffic periods. Such situations are thought to breed contempt and disregard for traffic signals, although documented evidence to support this argument is lacking. However, the evidence suggests that drivers are more apt to stop for a steady red signal, thus reducing the chances of an accident. Nevertheless, attempts should be made to reduce delay and driver frustration through the signal timing alternatives mentioned previously.

General trends among transportation agencies include the recent surge in litigation and growing concern for reducing liability exposure. Plaintiffs have sometimes argued that flashing signal operation was a casual factor in right-angle accidents at intersections. When this factor is coupled with allegations of limited corner sight distance, the road agency stands to lose a great deal of money.

To reduce agency liability exposure, it is necessary to identify and treat areas of risk. Results indicated the risk of right-angle accident occurrences at four-legged arterial intersections is higher when signals operate in a flashing mode than when they operate in normal mode. Thus, treatment could be justified from a risk management standpoint.

Gaberty and Barbaresso (1987) concluded that although right-angle accident frequencies should be used to determine whether the traffic signal should be flashing or normal. The following surrogate criteria may also be used.

1- Based on the functional classification and the intersection configuration results, the elimination of late-night flashing signal operation at four-legged intersections of two arterial roads was effective in reducing right-angle intersections.
2- If the volume ratio is 4:1 or less, the elimination of flashing signal operation should be considered.
3- The elimination of flashing signal operation should be considered until at least 3:00a.m. or until one hour past the closing time for bars, nightclubs, and taverns.

Kacir et al. (1993) and Kacir et al. (1995)

Based on a simulation experimental analysis, the TTI (1993) study presented a flowchart (Figure 1) that generalizes guidelines for implementing flashing signal operation. These guidelines considered only traffic volumes and accident history at the intersection in recommending signal mode for the intersection. The guidelines depend on the number of accidents occurring in the intersection in the two years prior to the consideration of changing to a nighttime flashing mode. This information might not be available, if flashing signal operation has not been considered for this intersection before. Furthermore, the guidelines ignored several important factors, such as turning movement, land use around the intersection, duration of flashing signal operation, time of day, intersection geometric design, lighting, sight distance, traffic composition and frequency of trucks, frequency of pedestrians, and speed limits. Also, the guidelines ignored the precautions that must be considered when starting and ending the flashing mode at the signalized intersection.

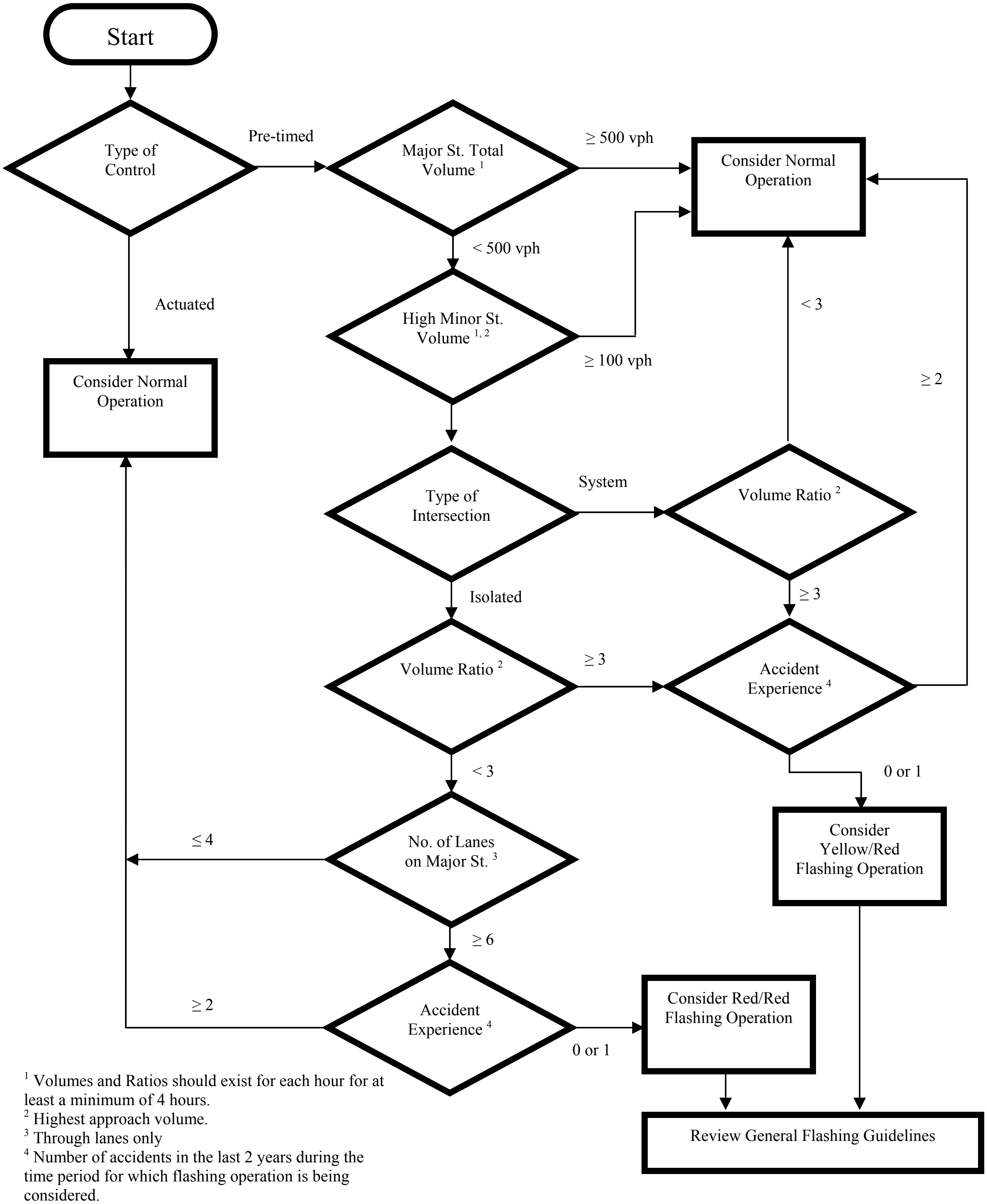


Figure 1: Flowchart for Implementing Flashing Operation during Low-Volumes Conditions (Source: Kacir et al. 1993)

GUIDELINES AND RECOMMENDATIONS

Based on the main findings of the literature review, it could be concluded that flashing traffic signals are not generally safe, and in most cases, accident rates tend to increase when they are implemented. The push to use flashing traffic signals could be contributed to three main reasons. The first reason is related to electrical power saving. The second is related to reducing the unjustified traffic delay during late night/early morning periods, when traffic volumes are low. Finally, although it was not documented in the literature, it was also argued that flashing signal operation can reduce the red-signal violation during late night hours. While the first reason could be justified, it is believed that delay and signal violations can be reduced by proper design for the signal timing in the normal operation. For example, in cases that actuated traffic signals are not available, pre-timed signals can be adjusted to work several plans for the peak, off-peak, and late night/early morning periods. Shorter cycle length is one possible solution for pre-timed signal to serve very low traffic volumes to reduce the unjustified stopping time at the empty intersections. Whenever the signal stopping time is reduced, it is expected that signal violations will decrease. Accordingly, it is recommended that whenever possible other traffic signal plans (e.g. shorter cycle length) should be tried and evaluated before implementing flashing traffic signal. Red/red flashing signals are generally safer to use than the yellow/red flashing signal, which possibly are more confusing to motorists. Red/red flashing signals force all traffic to stop at the intersection, which could be a successful measure for speed calming during late night/early morning operation. However, in many circumstances, stopping traffic on a major approach by a flashing red light may not be an efficient scheme.

Below are the main guidelines that should be considered when implementing flashing signal operation. Given these guidelines, we highly believe that engineering judgment will still play a significant role in deciding on implementing or removing flashing signal operation.

1- First of all, if flashing traffic signals are to be used in any city, <u>education</u> efforts should be performed to enhance driver knowledge about flashing traffic signals and the appropriate motorists' actions during each signal indication. It is generally believed that as more drivers become familiar with the flashing traffic signal, these drivers will be able to maneuver safely at intersections with flashing traffic signals, which could result in overall reduction in conflicts and accidents. This can mainly be done by a series of public service announcements and brochures on traffic control devices. Also drivers' exams should reflect that drivers need to be aware of these operating traffic controls.

2- Start and end times of flashing signal operations should be consistent for all the intersections that deploy such traffic control techniques. Careful attention should be given to study the best start/end time of flashing signal operation for all intersections considered for this type of operation. Previous studies have indicated that the start time of flashing signal operation should co-inside with the closing of night clubs/bars. Flashing traffic signals should start at least one hour after the closing of nearby bars and night clubs to ensure minimal interaction with pedestrians or drivers who might be under the influence of alcoholic drinks. These pedestrians and drivers might not be alert enough to realize the change of traffic signal operations or implement the right maneuver at these intersections.

Another factor to be considered is the shape and configuration of the flashing indicator; it should be uniformed for all intersections to minimize motorists' confusion. This is expected to further reduce driver confusion at intersections with flashing traffic signals.

3- Sight distance should always be studied when considering flashing signal operation and particularly yellow/red flashing signal, where motorists on the minor approaches (red flash) use their own judgment to cross the major approaches (yellow flash) of the intersection. The AASHTO Green Book (1990) should be used to study sight distance for intersections with yellow/red flashing signals. If sight distance is not satisfied, either normal signal operation or red/red flashing signal operation can be used. Sight distance calculations should consider that flashing signals are implemented during late night/early morning hours when motorists tend to be less alert and more stressful. Also, the visibility conditions during these hours are expecting to be lower than the morning hours.

4- Approach speed should be considered when deciding on implementing flashing traffic signals, especially yellow/red flashing signals. With the yellow/red flashing signal implementation, motorists on the minor approach are expected to cross the major approach based on their own safety judgment. The higher the traffic speed on the major approach, the harder it would be for motorists to make the right decisions on crossing the road. It is recommended that yellow/red flashing signals should not be applied if the speed (represented by 85 percentile speed or possibly speed limit) on the major street is greater than 35 mph. This speed limit on the major approach is expected to increase the safety of the intersection, where motorists on the major approach can respond to any risky, wrong, or unexpected crossing maneuvers of vehicles from the minor street. When speed at the major approach is higher than 35 mph, yellow/red flashing signal can be replaced by red/red flashing to insure that traffic on the major approach slow down when approaching the intersection.

5- Yellow/red flashing signals should not be implemented when the number of lanes on the major approach exceeds two for each direction. When the number of lanes on the major approaches exceeds two per direction, it will be more challenging for the traffic on the minor approach to decide on a safe gap to cross the major street. Crossing the major street would require motorists on the minor approaches to carefully observe all traffic on the different lanes of the major approach, which could be more challenging during late night hours when visibility conditions are low. When the number of lanes exceeds two per direction on the major street, red/red flashing signals could be applied. However, we recommend that normal signal operation is used when the total number of inbound lanes (including left turn lanes) of all approaches in the intersection exceeds eight. When the number of lanes increases, applying the first-in-first-out rule at the red/red flashing signal might be confusing and results in more conflicts (and probably accidents) among crossing traffic.

6- Traffic volume is the main factor that determines whether or not flashing signal operation should be used at any intersection. Average Daily Traffic (ADT) and average hourly traffic volumes during late night/early morning hours are commonly used to select whether flashing signal operation can be used or not at any intersection. Also, the volume ratio (major approach volume/minor approach volume) is also used to determine the type (mode) of flashing signal operation (yellow/red or red/red operation). Generally, there is no agreement on the values of volume or the volume ratio that can be used when selecting on using flashing signal operation or the flashing mode.

A new methodology is adopted as another approach to decide on using flashing signal operation and the mode of operation. The methodology is derived from the observation that flashing traffic signal operation mimics the control of traffic at intersections with stop sign and yield sign control, therefore it is necessary to make sure that precautions related to stop sign and yield sign operation are available at signalized intersections that use flashing traffic signals during low traffic volume periods. The methodology is based on traffic volume levels on the main and the secondary approaches of the intersection, where traffic volumes that are suitable for red/red flashing traffic signal should have the traffic volume ranges that work successfully under 4-way stop sign intersections. Similarly, traffic volumes levels suitable for yellow/red flashing traffic signals should be the same as those that work successfully under 2-way stop sign intersections.

The proposed methodology extends the current widely-used guidelines of the MUTCD 2003 and the Highway Capacity Manual 2000, which offer information for selecting the type of control at intersections based on traffic volumes to include flashing signal operation. Figure 2 gives the general guidelines for selecting the type of control at the intersection as a function of the peak-hour volumes in the intersection. Based on peak-hour volume values in the major and minor approaches of the intersection, the traffic control type can be selected, which could be traffic signal, all-way stop, and two-way stop. As shown in Figure 2, stop signs can handle up to 2000 vehicles during the peak hour on the major street as long as hourly peak traffic volume on the minor street is considerably low (about 150 vehicles per hour). Also, all-way stop sign operation can handle about 500 vehicles on both approaches during the peak hour.

Figure 2 can be extended to include selecting between normal and flashing operation of traffic signals. The effect of traffic volumes on selecting flashing signal operation can be justified in the same way that the type of traffic control is selected at the intersection.

However, since previous studies have indicated that motorists are less familiar with flashing traffic signals, and because flashing signal operations are usually applied during late night hours when motorists are typically more exhausted and stressful, it is suggested that the levels of traffic volumes (Figure 2) can be reduced by using a safety factor, Δ, that captures the differences between the operation of stop signs and flashing signals.

Additional factors that might affect a decision on selecting flashing signal operation at an intersection, such as accident rate, existence of pedestrians, traffic composition, land use, etc. can also be considered by adopting a factor of safety to reduce the traffic volumes that warrant the use of flashing signal operation. The value of the safety factor represents a reduction in the traffic volumes that warrant the use of flashing signal operation. It increases when more adverse conditions for flashing signal operation are expected at the signalized intersection. These adverse conditions are expected to make use of flashing signal operation unsafe or unsatisfactory. The value of Δ can be represented mathematically as follows:

$$\Delta = f(X_1, X_2)$$

where, X_1 and X_2 represent the set of quantitative and qualitative factors that affect the flashing signal operation at the intersection such as accident rate, turning movement, land use around the intersection, intersection geometric design, lighting, sight distance, traffic composition and existence of trucks, existence of pedestrians, speed limits, public awareness, etc.

It is generally difficult to determine the value of the factor of safety (Δ). However, it can be estimated based engineering judgment. We recommend a safety factor of the range of 50% can be used to reduce the limits of traffic volumes under which flashing signals can be operated during the late night/early morning (LN/EM) hours. Figure 3 shows an example of selecting the type of signal operation based on the LN/EM hourly volume for signalized intersections with 50% safety factor.

While the value of 50% might be questionable, we still believe that implementing flashing operation relies heavily on engineering judgment to evaluate the various situations; the traffic engineer can adjust this factor of safety value until he/she feels comfortable about the implementation.

Several advantages can be highlighted for the proposed approach:

- It depends on the prevalent methodology of selecting traffic control at intersections which can easily be understood by traffic engineers,
- It sets the minimum safe warrants that are required to guarantee safe and satisfactory operation of flashing signals at intersections with normal conditions.
- It is flexible and can accommodate a wide variety of signalized intersections with different configurations. Traffic engineers can easily modify the warrants of using flashing signal operations to impose additional safety concerns,
- The range of the values of Δ can easily be classified to represent different levels of safety while operating flashing signals.
- The factory of safety value Δ can be changed over time until traffic engineers feel that more and more drivers understand the indications of flashing traffic signals and react safely at the intersection.

7- When yellow/red flashing signals are in use, <u>advisory signs</u> can be posted on the minor street approaches (which have flashing red indicators) to warn approaching drivers on the minor street that traffic on the major street is not stopping when the signals are flashing. These advisory signs are expected to alert drivers and inform them about the correct action when they approach the intersection. These signs will be more significant when flashing signal implementation is relatively new in the city.

8- Last but not least, <u>accident patterns</u> (type, rate, and frequency) at the intersection in which flashing signal operation is implemented should be tracked and studied carefully. While previous studies have set limits on the rate of accidents that when exceeded, flashing signal should be converted to normal operation, these limits might not be applicable to all types of intersections. Also, political pressure from the public might have some impact after an accident occurs. The best way to investigate change in accident pattern due to using flashing signal operation is to continuously compare accident patterns at two similar intersections that are using flashing signal operation and normal signal operation, respectively.

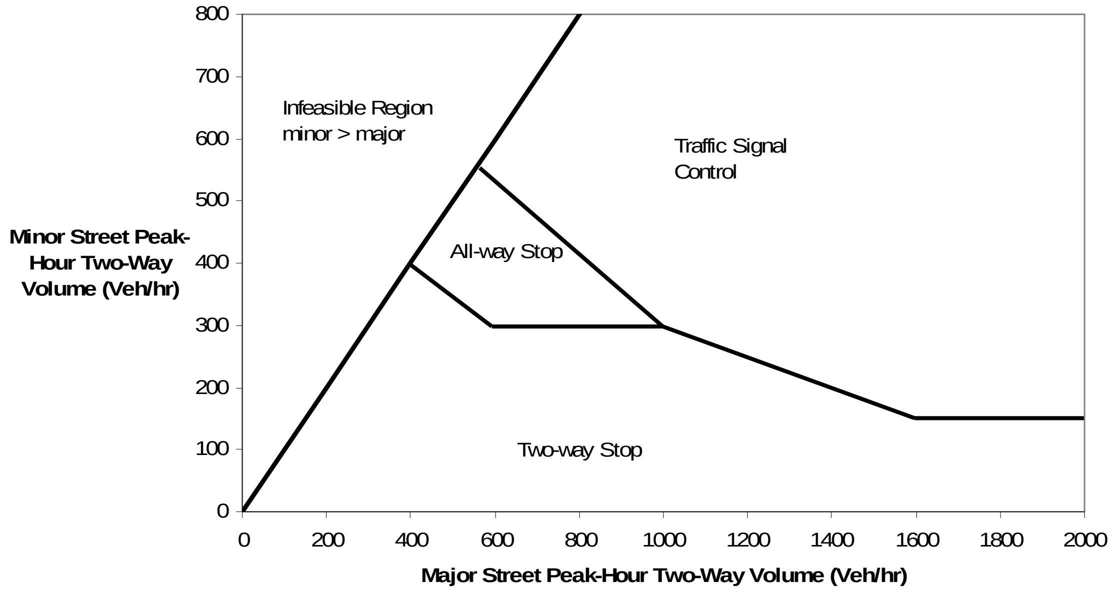


Figure 2: A sketch for the relation between the intersection control type and the peak-hour volumes as given in the Highway Capacity Manual (2000) page 10-21.

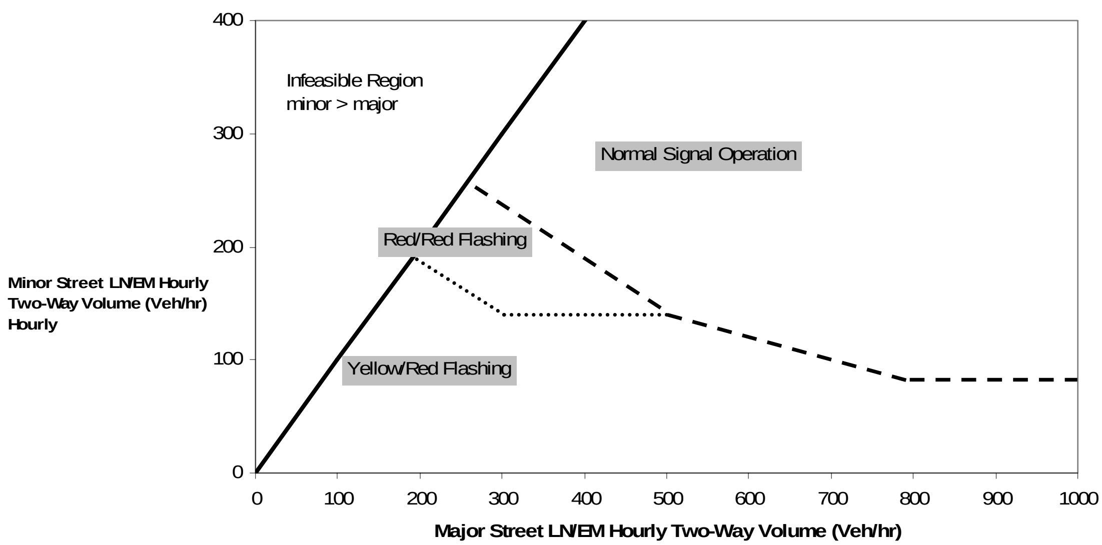


Figure 3: Illustrative example of the proposed methodology for selecting between the normal signal operation and the flashing signal operation at a signalized intersection (Factor of Safety = 0.5).

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